INT. J. REMOTE SENSING, 2000, VOL. 21, NO. 2, 409–415

Volumetric lidar return patterns from an old-growth tropical rainforest canopy

J. F. WEISHAMPEL

Department of Biology, University of Central Florida, Orlando, FL 32816-2368, USA; e-mail: jweisham@mail.ucf.edu

J. B. BLAIR

Laser Remote Sensing Branch, Code 924, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

R. G. KNOX

Biospheric Sciences Branch, Code 923, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

R. DUBAYAH

Department of Geography, University of Maryland, College Park, MD 20742, USA

D. B. CLARK

Department of Biology, University of Missouri—St Louis, St Louis, MO 63121-4499, USA

(*Received 10 March 1999; in final form 30 June 1999*)

Abstract. Rainforests represent the epitome of structural complexity in terrestrial ecosystems. However, measures of three-dimensional canopy structure are limited to a few areas typically < 1 ha with construction crane or walkway/platform access. An innovative laser profiling system, the Laser Vegetation Imaging Sensor (LVIS), was used to map canopy structure (i.e. based on height and vertical distribution of laser returns) of a tropical rainforest in Costa Rica. Within a $\approx 1\,km^2$ area of mature rainforest, canopy top height ranged from 8.4 to 51.6 m based on the altimeter measures. The laser return density was most concentrated in the horizontal layer located 20–30 m above the ground. Spatial patterns of the return were found to be isotropic based on north–south versus east–west vertical return profiles and exhibited properties of self-similarity.

1. Introduction

Vertical and horizontal patterns of forest canopies, the heterogeneous distribution of canopy components (i.e. leaves, twigs, branches, trunks, lianas, epiphytes, etc.) and spaces (i.e. structural openings between components occasionally from broken branches or treefall gaps), produce microclimatic (e.g. light, temperature, humidity) gradients. These feed back into biological/ecological processes (e.g. growth,

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals/tf/01431161.html

competition, mortality) thereby further defining organizational properties. The complexity of this architecture is most pronounced in tropical rainforests which are classically described as cathedral-like and have often been misrepresented as being stratified or layered (see Hallé *et al.* 1978, Richards 1996). These canopies are home to the majority of known species (Erwin 1995) and provide the primary surfaces of energy and matter exchange between the atmosphere and the largest reserves of aboveground carbon (Perry 1994). The three- and four-dimensional characterization and visualization of these dynamic systems have been deemed an essential avenue of future canopy research (Nadkarni and Cushing 1995).

2. Methods

2.1. *Data acquisition using an airborne imaging laser altimeter*

Measures of vertical canopy structure (e.g. MacArthur and Horn 1969, Brown and Parker 1994) which tends to be fairly heterogeneous are typically limited to a relatively few point locations in a forest stand. However, recently developed laser profiling or scanning systems (Nilsson 1996, Lefsky *et al.* 1999) can provide similar metrics across forested landscapes. These active systems record the time-varying amplitude of the return signal from a wide-beam laser pulse. The resulting waveform is a measure of the nadir-projected distribution of surface areas between the canopy top and the ground. This technology is being incorporated into the Vegetation Canopy Lidar mission (Dubayah *et al.* 1997, VCL 1999). Scheduled to launch in 2000, this satellite sensor will measure canopy structure globally. VCL mission objectives are to provide: (1) land cover characterization for terrestrial ecosystem (e.g. canopy height and aboveground biomass) and climate modelling; and (2) a global reference dataset of topographic spot heights and transects.

In late March 1998, LVIS (Blair *et al.* 1999), the airborne VCL simulator, flew over La Selva Biological Research Station in Costa Rica (figure 1). Flying at medium

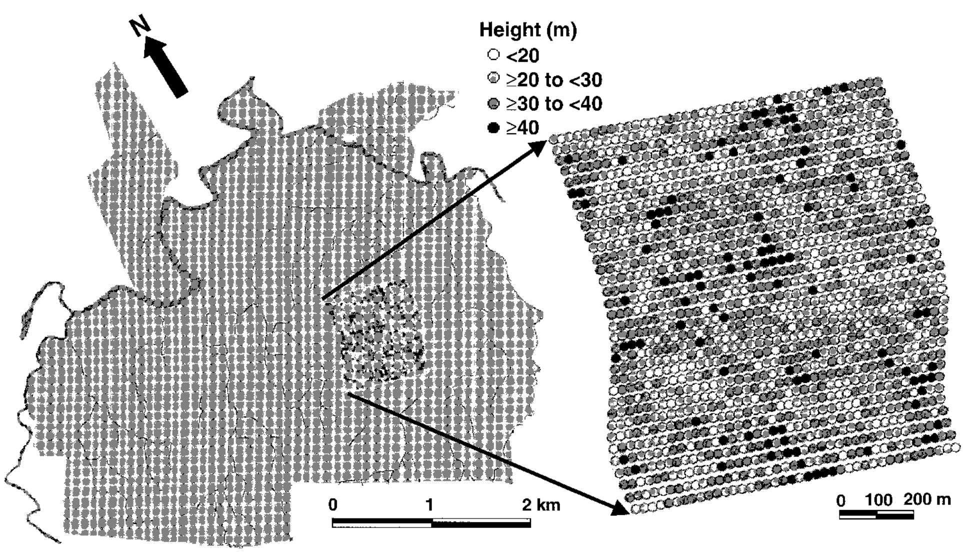

Figure 1. Area (≈ 1 km²) of non-overlapping LVIS footprints across a region of old-growth forest located upland from the Río Sarapiquí floodplain in La Selva, Costa Rica. Canopy heights, i.e. first laser return above background noise levels to peak of ground return, are designated by the white to black colour gradient.

altitudes, i.e. ≈ 8 km above ground level, this imaging laser altimeter mapped forest canopy patterns by recording reflectivity information from a 1 km across-track swath, comprising 80 overlapping, 25 m diameter laser footprints with a vertical resolution of ≈ 0.3 m. Thus, unlike its lidar predecessors which acquired narrow transects of data one or several footprints wide, LVIS is able to inventory entire watersheds and landscapes. Here, we analysed the three-dimensional spatial properties of the laser signals from a $\approx 1\,km^2$ area of old-growth tropical rainforest anthropogenically undisturbed in the post-Columbian era though subjected to fire in the late Holocene (Horn and Sanford 1992). McDade and Hartshorn (1994) have designated this section of forest as primary.

2.2. *Textural pattern analysis*

The volumetric nature of the laser return lends itself to pattern analysis at landscape scales unprecedented for forest canopies. Changes in density of return at different scales were measured using a gliding box lacunarity algorithm (Plotnick *et al.* 1996). Lacunarity is related to fractal geometry and has been used to quantify textural patterns in single trees (Martens *et al.* 1993) and to monitor change in rainforest landscapes (Weishampel *et al.* 1998). For a binary image, it represents 'gappiness', i.e. the ratio of the variance of the number of occupied sites to the square of the mean number of occupied sites found within windows of a particular size.

For this analysis, the non-rectilinear grid of footprints shown in figure 1, was realigned into a regular grid. Vertical return for each laser pulse was aggregated into ≈ 0.9 m bins. These changes are depicted by the three-dimensional visualizations in figure 2 where each $25\,m \times 25\,m \times 0.9\,m$ voxel value was computed using a linear interpolation involving the eight data values at the corners of the grid cell. A voxel is the smallest distinguishable box-shaped part of a three-dimensional space, a volumetric pixel. To generate binary patterns for lacunarity analysis, returns in each 0.9 m vertical bin above and below the median return energy for each footprint were considered occupied and unoccupied, respectively, in a similar vein, but with a finer vertical resolution, to the methodology described by Parker (1995).

To determine the presence of anisotropy in the forest profile, lacunarity was analysed for west–east (figure 2(*a*)) and south–north (figure 2(*b*)) vertical slices of the return volume. Each slice corresponded to a row or column of footprints (i.e. 40 or 34 footprints long, respectively, and 66.6 m high) from the regular grid with a minimum window size of 25 m wide x 0.9 m high. Lacunarity of horizontal slices (figure 2(*c*)) was measured to show variation in canopy opening (or gap) patterns as the lidar penetrates the forest. The minimum window size was $25\,m \times 25\,m$. These patterns from the 0.9 m thick slices were averaged within 10 m intervals. Finally, lacunarity of the overall return volume (figure 2(*d*)) was determined using a three-dimensional approach. The minimum box size across the approximate $1000\,m \times 850\,m \times 66.6\,m$ volume (assuming all 25 m footprints were regularly spaced) was $25\,m \times 25\,m \times 0.9\,m$. To examine scaling properties in these calculations, two-dimensional window sizes ranged from 1 to 400 times the area of the minimum window, and three-dimensional box sizes ranged from 1 to 8000 times the volume of the minimum box. With the three-dimensional lacunarity, a Monte Carlo routine was run to depict where and to what extent the return patterns differ from those expected with random permutations of the binary volume. For each waveform, occupied voxels were randomly arranged within the region above the noise threshold, i.e. between the detected canopy top and ground. To generate $P < 0.01$ envelopes,

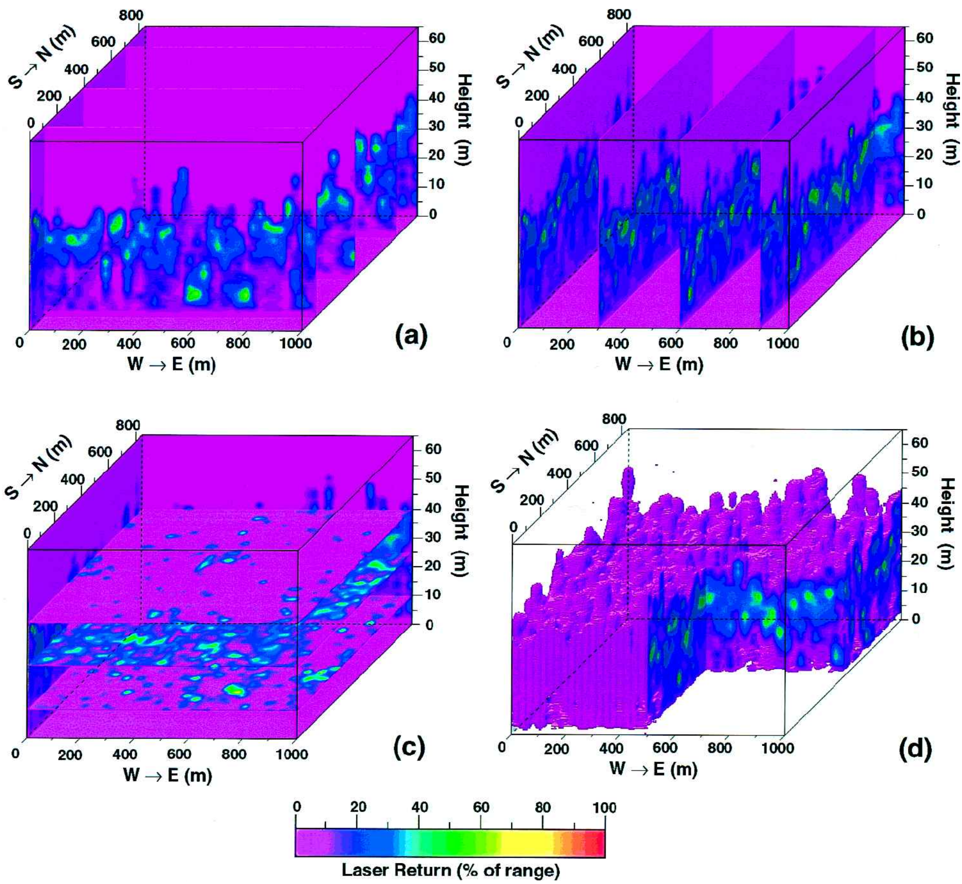

Figure 2. Volumetric renderings of the LVIS data from the $\approx 1\,km^2$ rainforest area depicting vertical (*a*) and (*b*) and horizontal (*c*) cross-sections and canopy rugosity (*d*). The *z*-axis is exaggerated to emphasize the vertical dimension.

100 of these neutral volume models were analysed and the minimum and maximum lacunarity were determined for the range of box sizes.

3. Results and discussion

Using a thresholding approach to discriminate between the canopy and ground, the mean canopy height of the 1360 footprints was 29.6 m with a standard deviation of 7.1 m. Canopy height ranged from 8.4 to 51.6 m. Height was calculated as the difference between the first return above background noise and the peak of the last return. Because the laser footprint size, i.e. $\approx 1960\,m^2$, is larger than most tropical canopy gaps at La Selva which are typically $< 200\,m^2$ (Denslow and Hartshorn 1994), no gaps that reached the ground were detected. Similarities between lacunarity for the south–north and west–east vertical slices (figure 3(*a*), (*b*)) suggest that the canopy is isotropic. Although light distributions around tropical forest gaps are anisotropic when comparing north–south versus east–west directions (Canham *et al.* 1990), simulated vertical growth in archetypal shade-intolerant and shade-tolerant trees in tropical latitudes was found to be isotropic (Weishampel and Urban 1996).

Horizontally (figure 3(*c*)), however, laser returns were most concentrated in the

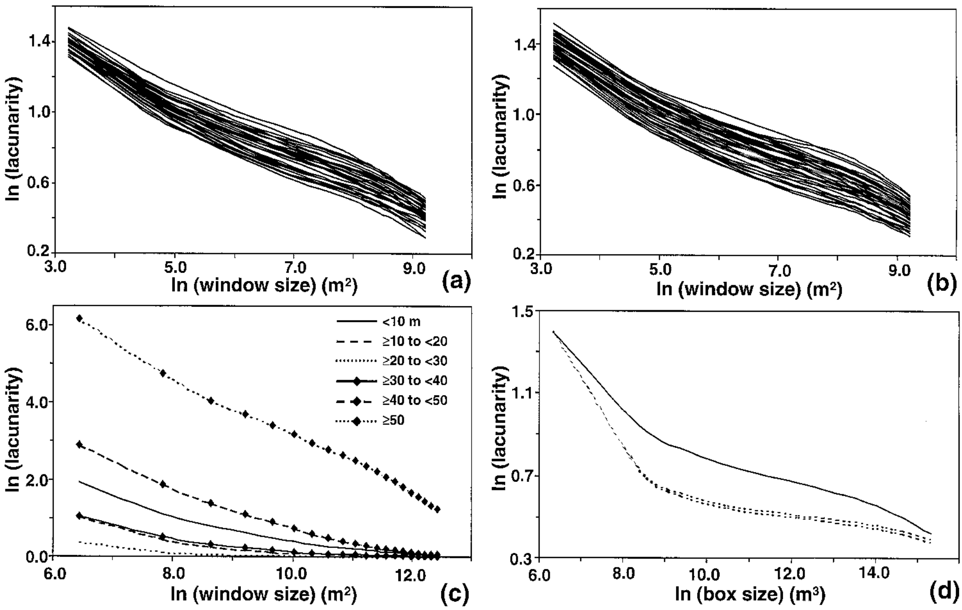

Figure 3. Textural patterns corresponding to 34 and 40 vertical slices one footprint (≈ 25 m) wide ((*a*) and (*b*), respectively) and horizontal slices ≈ 0.9 m thick averaged into 10 m canopy layers (*c*). The three-dimensional lacunarity pattern (*d*) is shown with the solid line. The two dotted lines represent random confidence envelopes ($P < 0.01$).

20–30 m stratum of the canopy as indicated by the lowest lacunarity values for the minimum window size. This corresponds to measures by Clark *et al.* (1996) who found that the median canopy height along replicated transects across La Selva was 23 m. Moving above or below this layer, the proportion of canopy to non-canopy decreased; hence the initial lacunarity values increased. Lacunarity was consistently above the random envelopes (figure 3(*d*)) indicating a greater relative clumping of return at all scales. For the three-dimensional analysis, the lacunarity curve was nearly linear which suggests that the distribution of laser return approaches self-similarity (Cheng 1997); this means that coarse-scale patterns of laser return resemble fine-scale patterns. However, the divergence from self-similarity indicates that forest structure may be better represented as multifractal as was found with binary two-dimensional rainforest gap maps from Barro Colorado Island in Panama (Solé *et al.* 1994).

These methods simply demonstrate a few ways that these data can be analysed. We took the general box-counting approach for tree crowns described by Zeide (1991), who mentioned that it could feasibly only be applied to a few individual trees. There is a myriad of uses for these new types of remotely sensed data. Information on canopy structure is critical in determining properties related to: atmospheric boundary layer, micro-meteorological, successional, arboreal habitat, and phenological conditions. Heretofore, such data have been unavailable at landscape scales.

Acknowledgments

We wish to thank: Michelle Hofton for geolocating the laser footprints; Jason Godin, Nancy Casey-McCabe, and the Organization for Tropical Studies for GIS and data processing assistance. Support was provided via the NASA Earth System Science Program (ESSP) award to the University of Maryland subcontracted to the University of Central Florida (Z64 4403).

References

Blair, J. B., Rabine, D. L., and Hofton, M. A., 1999, The Laser Vegetation Imaging Sensor (LVIS): A medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography. *ISPRS Journal of Photogrammetry and Remote Sensing*, **54**, 115–122.

Brown, M. J., and Parker, G. G., 1994, Canopy light transmittance in a chronosequence of mixed-species deciduous forests. *Canadian Journal of Forest Research*, **24**, 1694–1703.

Canham, C. D., Denslow, J. S., Platt, W. J., Runkle, J. R., Spies, T. A., and White, P. S., 1990, Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. *Canadian Journal of Forest Research*, **20**, 620–631.

Cheng, Q., 1997, Multifractal modeling and lacunarity analysis. *Mathematical Geology*, **29**, 919–932.

Clark, D. B., Clark, D. A., Rich, P. M., Weiss, S., and Oberbauer, S. F., 1996, Landscape-scale distribution of understory light and forest structure in a neotropical lowland rain forest. *Canadian Journal of Forest Research*, **26**, 747–757.

Denslow, J. S., and Hartshorn, G. S., 1994, Tree-fall gap environments and forest dynamic processes. In *La Selva: Ecology and Natural History of a Neotropical Rain Forest*, edited by L. A. McDade, K. S. Bawa, H. A. Hespenheide and G. S. Hartshorn (Chicago: The University of Chicago Press), pp. 120–127.

Dubayah, R., Blair, J. B., Bufton, J. L., Clark, D. B., JàJà, J., Knox, R., Luthke, S., Prince, S., and Weishampel, J., 1997, The Vegetation Canopy Lidar Mission. In *Land Satellite Information in the Next Decade II: Sources and Applications* (Bethesda, Maryland: American Society for Photogrammetry and Remote Sensing), pp. 100–112.

Erwin, T. L., 1995, Measuring arthropod biodiversity in the tropical forest canopy. In *Forest Canopies*, edited by M. D. Lowman and N. M. Nadkarni (New York: Academic Press), pp. 109–127.

Hallè, F., Oldeman, R. A. A., and Tomlinson, P. B., 1978, *Tropical Trees and Forests: an Architectural Analysis* (New York: Springer-Verlag).

Horn, S. P., and Sanford, R. L., Jr, 1992, Holocene fires in Costa Rica. *Biotropica*, **24**, 354–361.

Lefsky, M. A., Harding, D., Cohen, W. B., Parker, G., and Shugart, H. H., 1999, Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA. *Remote Sensing of Environment*, **67**, 83–98.

MacArthur, R. H., and Horn, H. S., 1969, Foliage profile by vertical measurements. *Ecology*, **50**, 802–804.

Martens, S. N., Borel, C. C., and Gerstl, S. A. W., 1993, High fidelity computer reconstructions of tree canopy architecture. *Bulletin of the Ecological Society of America*, **74**, 345.

McDade, L. A., and Hartshorn, G. S., 1994, La Selva Biological Station. In *La Selva: Ecology and Natural History of a Neotropical Rain Forest*, edited by L. A. McDade, K. S. Bawa, H. A. Hespenheide and G. S. Hartshorn (Chicago: The University of Chicago Press), pp. 6–14.

Nadkarni, N. M., and Cushing, J. B., 1995, Final report: designing the forest canopy researcher's workbench: computer tools for the 21st century. International Canopy Network, Olympia, Washington.

Nilsson, M., 1996, Estimation of tree heights and stand volume using an airborne lidar system. *Remote Sensing of Environment*, **56**, 1–7.

Parker, G. G., 1995, Structure and microclimate of forest canopies. In *Forest Canopies*, edited by M. D. Lowman and N. M. Nadkarni (New York: Academic Press), pp. 73–106.

Perry, D. A., 1994, *Forest Ecosystems* (Baltimore: Johns Hopkins University Press).

Plotnick, R. E., Gardner, R. H., Hargrove, W. H., Prestegaard, K., and Perlmutter, M., 1996, Lacunarity analysis: a general technique for the analysis of spatial patterns. *Physical Review E*, **53**, 5461–5468.

Richards, P. W., 1996, *The Tropical Rain Forest*, 2nd edn (Cambridge: Cambridge University Press).

SOLÈ, R. V., MANRUBIA, S. C., and LUQUE, B., 1994, Multifractals in rainforest ecosystems: modelling and simulation. In *Fractals in the Natural and Applied Sciences*, edited by M. M. Novak (Amsterdam: Elsevier Science), pp. 397–407.

VCL, 1999, available as: http://www.inform.umd.edu/Geography/vcl/index.html

WEISHAMPEL, J. F., SLOAN, J. H., BOUTET, J. C., and GODIN, J. R., 1998, Mesoscale changes in textural properties of 'intact' Peruvian rainforests (1970s–1980s). *International Journal of Remote Sensing*, **19**, 1007–1014.

WEISHAMPEL, J. F., and URBAN, D. L., 1996, Linking a spatially-explicit gap model with a 3-dimensional solar routine to simulate latitudinal effects. *Ecological Modelling*, **86**, 101–111.

ZEIDE, B., 1991, Fractal geometry in forestry applications. *Forest Ecology and Management*, **46**, 179–188.